Ice Management Manual

Ministry of Natural Resources
Ontario

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Preface

Acting on numerous requests for guidance and procedures for dealing with chronic ice problems in Ontario, the Conservation Authorities and Water Management Branch initiated an ice jam program in 1980. The prime objective of the program was to prepare a manual that would include guidelines and procedures for monitoring, predicting and acting on ice break-up and jamming on rivers in Ontario where the history of ice jams is frequent and well-known.

The Branch initiated co-operative projects with the Grand River, Ganaraska Region and Credit Valley Conservation Authorities for the purposes of identifying factors affecting ice jams and collecting other pertinent data such as ice cover, air temperature and streamflow data. In addition, special investigations on specific ice jam problem areas in northern Ontario such as the Goulais River and Town Creek in Timmins were carried out. It was intended that data and information obtained from these activities would be used in the preparation of this manual.

The program also reviewed and documented the history of ice jam problems and remedial measures in the Province, including the documentation of the causes and extent of the events in February, 1981.

This manual is the product of all activities and studies that have been undertaken under this program since 1980. It is hoped that the information provided will be useful in preventing and dealing with the many ice jam related problems that are encountered in the Province.

November, 1984

M.R.Garrett, Director
Conservation Authorities and
Water Management Branch

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Introduction

When rivers become jammed with broken, thawing ice which flows faster than the channel can carry it away, flooding occurs. Ontario's history of ice jams is well known; but the frequency and severity of the problem is increasing. Ice jams caused serious and widespread flooding in Ontario in February, 1981. Dover Township and Port Hope are specific examples of areas that suffered from disastrous flooding also in 1979 and 1980.

There are two sets of problems: the first may occur during freeze-up, when the amount and type of ice forming might impede the flow of water, which then backs up and overflows. The second trouble occurs when ice begins to break up in Ontario's waterways — not only during the annual spring thaw, but also during extreme and prolonged temperature fluctuations earlier in the winter. These abnormal fluctuations, together with a recent trend towards significantly colder winters, have exacerbated the problems associated with ice jams. An increasing number of requests for guidance and procedures to deal with these problems — not only chronic but often now acute problems — resulted in an Ice Jam Program, initiated in 1980 by the Ministry of Natural Resources' Conservation Authorities and Water Management Branch and the Conservation Authorities.

This manual is the result of the program's prime objective: to provide preliminary information and guidelines which can be used to determine the proper procedures for predicting, preventing, and dealing with ice-related flooding.

There are a number of factors generally common to all ice jam situations, and there are many similarities to be found in the conditions prevailing just prior to the jams, wherever they may occur. The studies of these factors and conditions, based on experience since 1960, have provided much of the information for this manual. Other up-to-date information since 1980 has also been obtained through the Ice Jam Program.

Each situation and location is, however, different; each area will have a unique combination of variables in its particular equation. Each area must, therefore, carry out its own data-collection program, which is necessary for determining the correct method of dealing with its own particular problem, as well as estimating the relative costs and benefits involved. It is essential to understand that, without this data (some of which can be collected from existing records, but much of which can only be determined by a monitoring program), the prevention of recurring problems is virtually impossible. The only alternatives are attempts to improve the situation after it has occurred, which are usually unsatisfactory.

Section 1 of this manual outlines briefly the historical patterns and changing trends relating to ice-jam floods in Ontario.

Section 2 summarizes the conditions causing ice-jam floods.

Section3 gives detailed descriptions of the factors involved in freeze-ups and the different kinds of ice formation that generally lead to problems.

Section 4 explains the causes of and techniques for predicting break-ups.

Section 5 lists the essential data to be collected through monitoring programs.

Section 6 assesses the success of remedial measures that have been practiced to date.

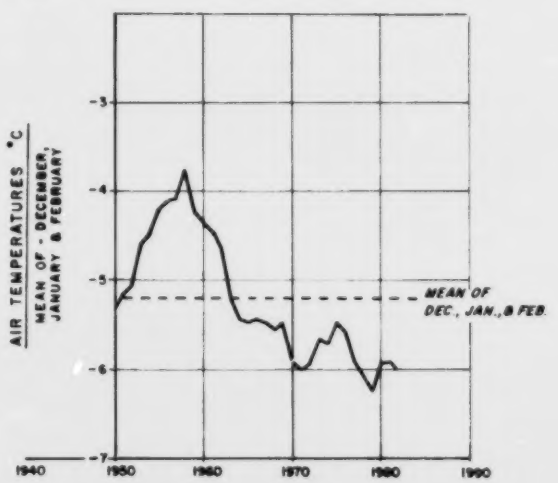
Section 7 summarizes the overall principles of ice control, and is followed, finally, by references and a bibliography (Section 8).

1
Historical Patterns and Changing Trends

Newspapers are the main source of historical records from which the frequency of recurring ice-related floods has been determined. This source has been useful in providing flood dates which can then be compared with weather reports from Environment Canada for the same periods. In this way, it has been possible to determine whether the problems were brought on by a sudden freeze or a sudden thaw.

There was a general decline in the frequency of ice-related floods in the 1950s. This coincided with a considerably warmer trend in winters during that decade. See Figure 1.

Figure 1



* TEN YEAR MOVING AVERAGES (1941 to 1950 plotted as "1950")

TREND IN WINTER TEMPERATURES

* Malton International Airport data, courtesy of T.J. Moyer.

Since then, however, the warming trend has reversed markedly, and there is evidence that this trend towards colder winters will continue for some time. The winter of 1979 and those since have been colder than average during the months of December, January, and February by almost one whole degree Celsius (Figure 1). During these coldest months, however, there have also been occasional and rapid thaws, which continued for several days.

The data show that ice-jam floods have been immediately preceded by rapid changes in weather and by colder than average winters. This trend is expected to contribute to continuing and increasingly frequent ice-related floods in the next ten years. Several improved ice management techniques do exist, however, and this manual indicates how they may be applied successfully to the situations in Ontario.

Typical problem in rural areas.

2 Conditions Causing Ice-Jam Floods

2.1 Two Basic Causes

Ice jams are the result of two basic causes: (i) the freezing up of rivers, and (ii) the break-up of ice during sudden and prolonged changes in weather conditions. In order to predict and prevent floods, an understanding is required of the climatic conditions and the hydraulic factors which can either assist in forming a protective cover or which can cause problems during freeze-up and break-up periods.

2.2 Velocity

Ice jams are caused by the accumulation of too much ice, carried by too much water, and in too short a time. Wherever the rate of supply of ice and water together exceeds the capacity of the river channel to transport it, a jam is imminent.

2.3 Type of Ice

The quality of the ice affects its ability to jam. Hard, blue ice is far more prone to jam than other softer forms, such as slush ice or frazil, which cause freeze-up problems. Slush ice in vast quantities is produced by snow falling and trying to freeze in open water. It has the consistency of wet cotton-batting; it is extremely difficult to handle and may cause severe restrictions of water flow. Frazil is a mass of frozen water particles which stick to each other and everything they touch (Plate 1). Frazil develops when water with no ice cover becomes super-cooled — that is to say, when it cools to below freezing (about -0.05C), but where there is at the same time sufficient air and water movement to: (i) prevent a solid ice cover from forming; and (ii) create an ice-particle blizzard. These particles can build up very rapidly indeed, especially on a rocky bottom, turning into what is called anchor ice. When this happens, the water-carrying capacity of the river can be reduced by 30 per cent within a period of three or four hours, as observed on the Niagara River.

2.4 Likely Sites

Ice jams are most liable to occur when there are:

sudden reductions in the water velocity caused by a widening or deepening of the river channel;

sudden changes in the direction of the flow;

constrictions in the river where it narrows, such as at bridges and their approaches.

2.5 Land Development

Urban development, land drainage, and deforestation all accelerate the rate of run-off — a situation which increases the probable frequency of ice jams.

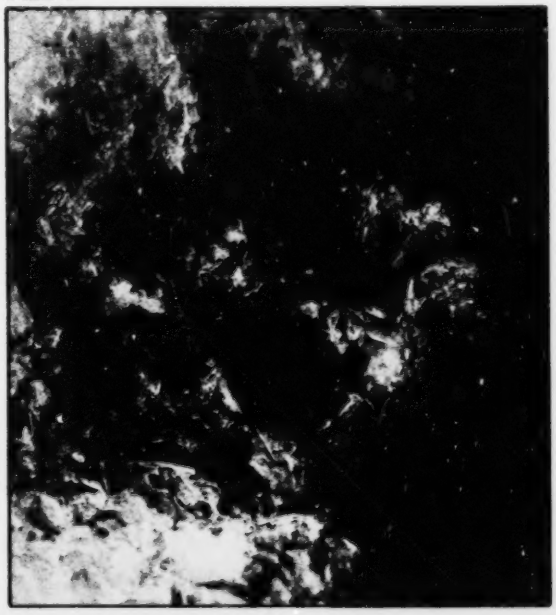
2.6 Dam Removal

Many streams in conservation areas once had mill ponds. They were formed by dams, which helped control ice jams. Today, however, many of these aids have been removed, filled in or have failed because of poor initial design.

2.7 Freezing from the Bottom Up

Where velocities, flows, and temperatures are all very low, a stream (such as Town Creek in Timmins, for example) will tend to freeze from the bottom up. The channel becomes full of ice, and incoming water flowing over its surface freezes rapidly on top. Given a sudden and prolonged thaw, the increased amount of water from the melting ice has nowhere to go, and floods. As the water softens and erodes the ice, some of it will float and cause jams at constrictions in the river, adding further to the flooding problem.

Plate 1



Frazil particles sticking together.

3
Factors Leading to Flooding During Freeze-up

All rivers in Ontario try to form an ice cover each winter, and this is a good feature, insulating the water from the air. The ability of a river to form an ice cover is dependent on the climate, however, which may fluctuate erratically within a period of only a few days, except in the more northerly rivers where the climate is more constantly cold.

These erratic weather patterns confuse an understanding of the measures required for managing ice jams. For example, two solutions used in the St. Lawrence (International Section) and Niagara Rivers appear, at first sight, to be contradictory. In the St. Lawrence, where a cover once formed will remain all winter, velocities are controlled to make the cover form as quickly as possible. In the Niagara, however, where the climate and storms on Lake Erie may cause frequent break-ups, velocities are controlled to prevent ice-cover formation

A strong, smooth ice cover extending from shore to shore is the most desirable. But it is seldom attained because, while the cover is trying to form, a number of factors can influence the process — such as temperature and wind chill, frazil, anchor ice, velocity, and snowfall. The significance of each is now examined.

3.1 Temperature and Wind-chill

Water temperatures drop more slowly than those of the air. In bays and quiet water areas where velocity is 0.1 metres per second (m/sec) or less, a surface cover will form first. This is important to bear in mind when choosing flood-preventive measures, as the first to freeze is the last to thaw, because of the greater thickness of ice.

Water is also subjected to progressive chilling as it proceeds downstream. Being warmest at the source, flowing waters can, therefore, be several degrees warmer than at the mouth.

With average temperatures of -6C and normal winds of 16 km/hr, river temperatures will drop 0.3C per day. Wind-chill factors, however, can affect these averages markedly, where the water temperature will drop as much as 2C in one day when severe wind-chilling of -30C or more occurs. This combination is reached with the following conditions:

-18 C air temperature and winds of 19 km/hr (12 mph)
-12C air temperature and winds of 32 km/hr (20 mph)
-10C air temperature and winds of 56 km/hr (35 mph)

3.2 Frazil

Once the flowing water at the source has dropped to about 0C, however, wind-chill combinations of -18C or colder will be sufficient to produce super-cooling — and hence frazil, as follows:

-6C and winds of 28 km/hr (17 mph)
-10C and winds of 16 km/hr (10 mph)
-14C and winds of 9 km/hr (5 mph)

Once super-cooling starts, with these wind-chill combinations, the open water area will create about 0.04 cubic metres of ice per square metre per day (7).* During a 50-day period of such weather, one square metre of open water would produce two cubic metres of ice.

When an ice cover forms over flowing water, however, its thickness normally reaches 0.5 metres and, by insulating the water from the air, reduces ice production to only 25 per cent of the amount of open water.

**Numbers in parentheses refer to papers in Section 8 on Selected References.*

3.3 Anchor Ice

Anchor ice begins forming on the bottom of rivers as soon as super-cooling begins. The increased volume of ice and the roughness of its surface raise the water level and impede its flow (frictional resistance). This decreases the flow by as much as 30 per cent in a few hours, which could choke the river and cause severe back-up problems.

3.4 Pancakes

Both anchor ice and frazil may, however, come to the surface and form 'flocs', which freeze together to form a 'pancake'. If the velocity is 0.7 m/sec or less, the pancakes will continue to grow in width and thickness to 100 m or more in diameter, and 40 mm thick in the space of eight hours when there are wind-chills of -18C (7). Eventually, the pancakes will come to rest against an island, bridge-opening or where the current may be slow enough for an ice cover to form. More pancakes following may slide either under or over the first, until they also come to a halt and, if the speed of the current is low enough, they will form the desired ice cover which extends rapidly upstream.

If, on the other hand, there is a long series of rapids upstream, the open water does not form a smooth, strong ice cover but continuously manufactures chunky, uneven ice that does not remain on the surface. This can create hanging dams which cause huge water-level increases. (Plate 2). In the St. Lawrence River, for example, the ice generated in the Long Sault Rapids in the past caused the water level to rise about 15 metres, sometimes flooding the main street of Cornwall. This was prior to the building of the Power Project, which was designed to form an ice cover and eliminate the ice-forming capability of the Rapids.

3.5 Snowfall

Falling directly or blowing into flowing water, snow will accelerate the water's chilling rate, forming masses of slush ice, which tends to cause jamming.

Also, snow falling on top of a layer of insufficiently thick or strong ice will insulate it from the air and may stop further ice growth entirely. This will prevent the formation of a strong ice cover. A weak ice cover will tend to break easily and cause jamming.

3.6 Velocity

The slope of the river affects the velocity and the extent to which sub-freezing air mixes with the water. In other words, the steeper the slope, the greater the increase in chilling rate — and, therefore, the quantities of frazil and anchor ice formed.

3.7 Conclusion

The period when ice is trying to form a cover is a critical one. It should be observed carefully as soon as the water temperature reaches 2C, and watched continuously until the ice extends solidly from shore to shore. Problems will develop with severe wind-chilling conditions and may be compounded by heavy snow. It is possible to have several cycles of freezing and thawing in the watersheds south of Barrie due to the cyclical variations in the weather. Techniques for predicting — and therefore preventing — ice break-up and jams due to these cyclical variations in the weather follow in Section 4.

Plate 2

Heavy surface ridging caused by ice pressures accumulating from ice generated in the rapids on the right of the photograph.

4
Break-up Factors and Predictive Techniques

Ice-jam flooding can be prevented only by first knowing how to predict when break-up is going to occur. Predictive techniques and preventive measures can only be employed, however, if the causes of ice break-ups are understood first.

As stated in Section 2.2, ice jams are caused by the accumulation of too much ice, carried by too much water, in too short a time. But how much is too much, and how short is too short?

Ideally, during the onset of longer days just before the spring equinox, the snow starts melting slowly, gradually increasing the water supply to the river. The increased flow causes the level to rise, increasing velocity; those portions of the river that froze last will lose their ice cover first. If this period continues over a period of several weeks, the main channel of the river opens, leaving a strip of shore ice on either side, which is also eroding and weakening. Because it was thicker to begin with, however, the shore ice takes longer to melt. As the river level rises, some of the shore ice will become detached each day, moving downstream. If the quantity of ice and water mixture is moderate, there will be no problems, even though the river mouths may still be frozen. Two or three weeks of such a weather pattern is enough time both to melt some of the ice and soften the rest. The slowly increasing flow will not, in this way, supply too much ice and water to any constricted sections at one time.

There have been a number of recent break-ups, on the other hand, where the entire process was compressed into several days only. Numerous jams and floods resulted (15). The causes were determined by studying the following factors during a one-week period prior to and a one-week period following the jam.

4.1 Number of Accumulated Degree-days of Melting

One 'degree-day of melting' occurs when the mean of the maximum and minimum air temperatures is +1C. In 1981, an accumulation within a four-day period of sixteen to twenty-three degree-days was enough to cause problems in most watersheds. In others, twenty-four to thirty-two degree-days occurred within a six-day period, which caused problems in all Ontario streams south of a line between Parry Sound and Ottawa (15). The melting rate was four to five degree-days each day. This rate of thawing continued unabated without any more periods of sub-zero weather which normally re-occur in spring

4.2 Precipitation Likely to Cause Break-up

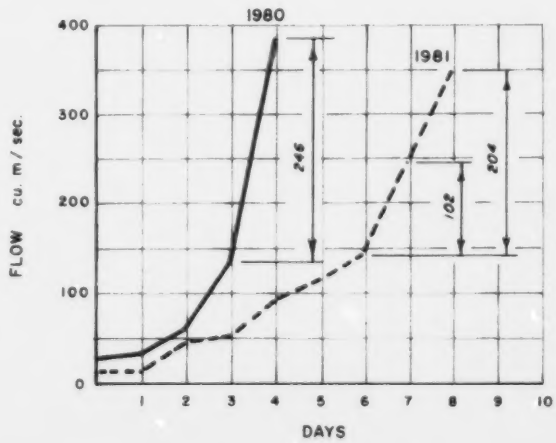
Precipitation generally in Ontario was less than 25 mm over the week prior to ice jams in February, 1981 (except in the Rideau area where it was 27 mm, and in the Moira and Ganaraska regions, where it was 54 mm). Depending on how much melting occurred before the rain, and depending on the water content of any snow already on the ground, the effects will vary. The worst combination is ten degree-days or more of melting, followed by 12 mm or more of rain in a 24-hour period falling on frozen ground or on snow of above-average water content.

Weather data are provided by the Streamflow Forecast Centre, together with a flood advisory, followed by a flood warning if events are likely to be worse than described. Weather forecasting is, however, generally inadequate for more than three days, which gives very little time to prepare for severe changes in weather.

4.3 Rate of Rise in Water Levels Due to Increased Flow

Rate of rise is obtained from the rate of increase in flow. This will vary from one watershed to another, but the factors which cause rising levels are the same and the results similar.

Figure 2

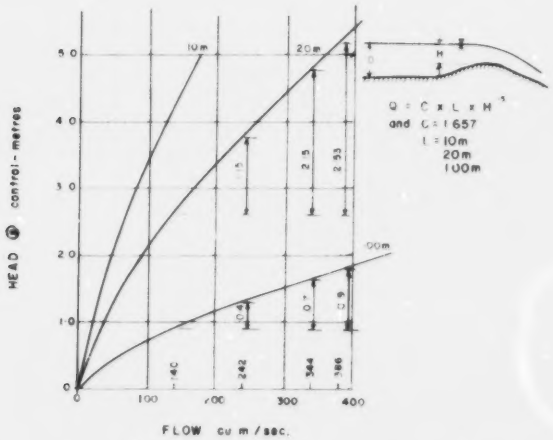


RIDEAU RIVER AT MANOTICK
HYDROGRAPHS DURING ICE BREAK-UPS

In the Rideau system, as an example, there have been two recent violent break-ups — in 1980 and 1981. On both occasions, the flow had been increasing gradually over 3-6 days to about 140 cubic metres per second (Figure 2). Following this gradual increase, however, an increase of 246 cu. m/sec occurred in only one day in 1980; and in 1981, an increase of 204 cu. m/sec in two days.

What must be determined is the lowest rate of increase in flow that has caused break-up. This figure can then be used as the threshold level signalling possible break-up. At this point, the effects on water levels should be examined.

Figure 3



TYPICAL WATER LEVEL DISCHARGE CURVES

Figure 3 shows the effects of increasing flows on water levels for various river widths. It is evident from these curves that constrictions tend to cause the greatest change in level.

The flow increased in 1981 from 140 to 242 cu m/sec in a single day. As seen in Figure 3, the water level would rise about 1.15 metres at a twenty-metre-wide section, whereas it would rise only 0.40 metres at a section 100 metres wide. On the basis of the increase in flow to 344 cu. m/sec in two days, the corresponding rises would be 2.15 and 0.74 metres respectively — probably enough to cause a number of problems.

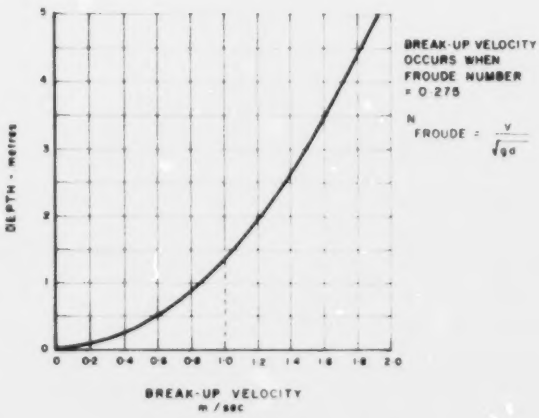
A one-metre rise is usually sufficient to pry the ice cover loose from the river banks in spring; but it would not necessarily move downstream or break up. That action depends on the velocities created or the topography of the river, together with such restraints as islands, bends or ice booms. Such a rate of rise would likely cause problems in narrow sections.

Based on the 1980 increase in flow to 386 cu. m/sec in one day, and referring to Figure 3 again, it can be seen that the water level at a twenty-metre-wide section would rise 2.53 metres; 0.87 metres at a 100-metre width. In this case, most of the ice in the river would move freely and break up also if velocities were high enough.

4.4 Number of Places where Velocities Exceed 1 m/sec

Predicting the locations where break-up will begin depends on the relationship between depth and the velocity required to cause break-up. Thus the key prevention is knowing the highest velocity that can occur without causing the main sheet ice to break up. As shown in Figure 4(a), the limiting velocity for prevention is about 1.0 m/sec, which will occur at a depth of 1.3 metres. As velocities usually exceed this value downstream of hydraulic control sections — generally narrow, fast water sections, weirs, or constrictions such as bridge piers — these will begin to break up first.

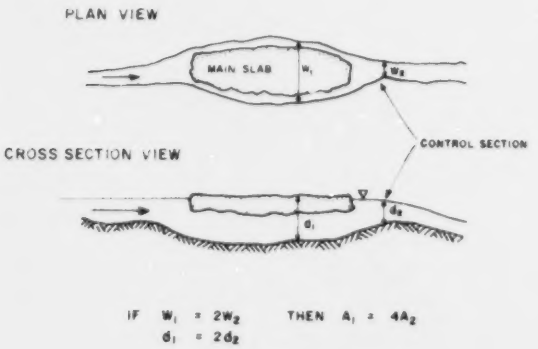
Figure 4a



DEPTH AND BREAK-UP VELOCITY CURVE

Water approaching a control section, where the river is wider and deeper, normally moves much more slowly than the break-up velocity, but accelerates as it enters the control section. If both the depth and width of a river upstream were, for example, twice that of the control section, this cross-sectional area would be four times greater than at the control section. (Figure 4b) Therefore, the flows can also be four times greater in volume before reaching critical velocity in the approaches. There will normally be some break up at the entrance to the control, and the main centre slab of ice will tend to float up with the rising water level (caused by the constriction, as discussed with reference to Figure 3). If the ice is raised one metre or more, it will try to move downstream. Unless the ice cover is retrained by an island, an ice boom, a pier, or the shores, the downstream edge may move into the break-up velocity zone.

Figure 4b

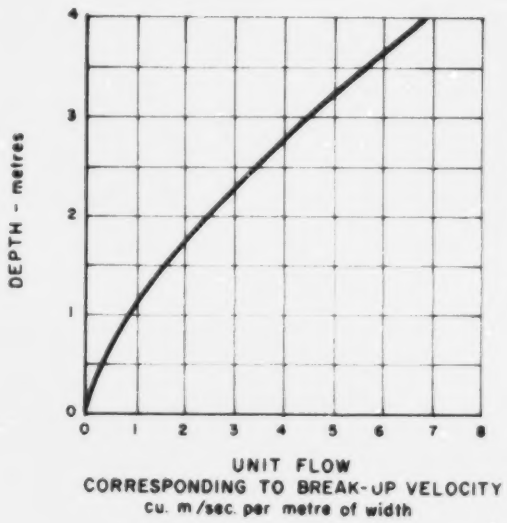


EFFECTS OF CONTROL SECTION

Break-up may also begin at the upstream end of an ice cover if other combinations of depth and velocity shown in Figure 4(a) exist. If the depth is three metres or less and the velocity reaches 1.5 m/sec or more, for example, the water tends to flow over the ice cover, causing pieces to break off and be forced underneath. Nothing can prevent break-up once this happens.

In Figure 5, the depth-to-break-up velocity relationship has been converted for convenience to a depth-to-break-up flow relationship (5). Based on a one-metre-wide section, the break-up flow becomes 1.3 cu. m/sec.

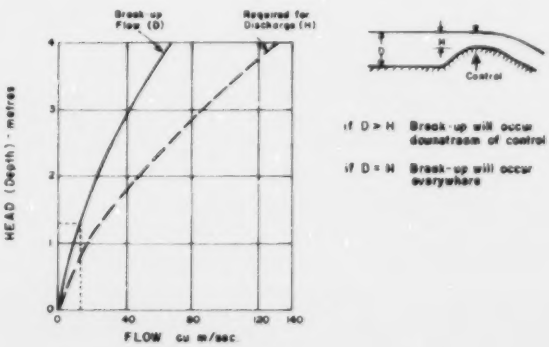
Figure 5



DEPTH AND BREAK-UP FLOW CURVE

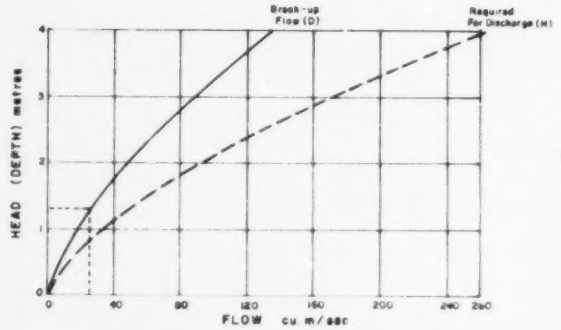
Figure 6 shows the depth-to-break-up flow relationship for a ten-metre-wide section. Shown simultaneously is the head-discharge relationship for a broad-crested weir control section (as in Figure 3). Similar relationships are shown for a 20-metre width in Figure 7.

Figure 6



DEPTH AND BREAK-UP FLOW CURVE FOR A 10 METRE WIDTH SECTION

Figure 7



DEPTH AND BREAK-UP FLOW CURVE FOR A 20 METRE WIDTH SECTION

Referring to Figure 6, the flow causing break-up would be 13 cu. m sec for a 10 m section. It would take place initially at, or downstream from, the control section because the same depth on the control section would indicate a flow of 25 cu. m sec. As flows increase, however, the velocity at the entrance to the constriction may rise above the break-up value; some ice will break off, and the ice cover will try to move downstream, assisted by the rising levels. As flows continue to increase, there will always be some rate of rise in level and some flow quantity that will cause general disintegration of large portions of the ice cover.

4.5 Partial Break-ups and Local Jams

Rising water levels and increasing velocities cause break-up to begin. Generally, this process takes two to three weeks, and the concentration of ice and water is not sufficient to cause jamming. However, if the process is compressed into a few days, a general disintegration will take place. Between these two extremes, partial break-ups may occur and cause local jams.

Wherever ice pieces accumulate in front of, and or under, an ice cover, a bending force is created which causes it to fail. Depending on the thickness and quality of the ice, a substantial local jam may result without causing a general disintegration of the entire cover. When this jam breaks, its pieces moving downstream to the next ice-cover may cause a new local jam, and this process may be repeated a number of times before the ice reaches the river's mouth. The time required to complete break-up is extended and there is less severe jamming in any one area.

A likely area for encountering these problems may be selected by following the procedures in Section 5.2.3 on On-site Observations.

4.6 Summary of Predictive Techniques

(a) Problems can be expected if there is an uninterrupted thaw of approximately twenty degree-days of melting during a very short period of time — ? to 5 days.

(b) Problems are likely in the event of precipitation of 12 mm or more in 24 hours, especially if this follows several days of melting, or if the ground is still frozen, or if the watershed has a large urban area.

(c) Rising water levels and increasing velocities cause break-up — a preliminary indication of possible trouble. A rise of one metre in 24 hours often causes break-up, and will always cause break-up where velocities are greater than 1.0 m sec.

(d) There is a specific break-up flow for every river, where large portions of the ice cover disintegrate generally. From limited information, it appears that the break-up flow is about 60 per cent of the 100-year flood flow.** Due to variations in ice quality and weather sequences, this percentage may vary from 50 to 70 per cent.

(e) Partial break-ups and local jams may occur due to broken pieces accumulating in front of, and or underneath, an ice cover, causing it to break by bending.

(f) The worst combination for break-up is a sudden thaw extending over four days, with rain. The resulting jams, however, will depend on how cold the winter has been, whether the ice is hard or soft, thick or thin. In the final analysis, it is the sequence of weather events that is critical.

***Flood levels based on the 1-in-100 year flood flow generally do not take ice jams into account. Thus, due to ice jams, these levels may be equalled or exceeded by a lesser flow (See Section 7.9).*

5
Data Collection and Monitoring of Ice Jam Floods

Before a cost-benefit analysis of remedial measures can be made, certain data need to be gathered. Some information may be obtained from Conservation Authority records; past dates and weather records can often be gathered through newspaper file searches and Environment Canada records.

Often, however, such past records will not, in themselves, provide sufficient information for making a satisfactory cost-benefit analysis, and it will be necessary to implement a monitoring program to gather information for the future. The most important basic piece of data comes from knowing the date the flood began.

5.1 Potential Benefits

Key benefits obviously come from reducing flood damage. The extent of past damage is assessed through answering the following questions:

(a) How many properties were affected, and what were their values?

(b) What was the cost of a clean-up?

(c) How long did the problem last?

(d) How frequent have the problems been?

5.2 Determining the Solution

Effective management techniques vary from one watershed to another — sometimes even within a single watershed. In every case, however, the information required is the same. Before any appropriate and reasonable solutions can be determined, the following information is required:

5.2.1 Weather Information

The crucial two-week period for which information is required spans the week preceding and the week following the date the flood began. During those two weeks:

(a) What were the maximum, minimum, and daily average temperatures?

(b) What was the daily precipitation? Specify snow or rain, and the snow's water equivalent.

(c) How many degree-days of thaw preceded and followed the jam?

5.2.2 Hydraulic Information

Data on the rate of change of inflow and the consequent changes in water level and velocity are particularly important to obtain. In the same two-week period:

(a) What was the variation in the flows and levels in the vicinity of the jam? A graph of these factors must be plotted against time; readings must be taken at least daily, and preferably every six hours.

(b) What was the maximum water level? This will be influenced greatly by river bank height, river width, and ice quality.

5.2.3 On-site Observations

Some of the most useful information of all is simple eye-witness observation of what happened, answering the following questions:

(a) Where did the ice in the jam come from? Was it, for example, a local condition, or did it come from several kilometres upstream?

(b) How thick was the ice?

(c) What kind of ice was it? Hard and blue, soft and white, frazil or slush?

(d) Were there any large lumps, thicker than one metre? These may come from the downstream end of fast-water areas; they are important clues for detecting the solutions.

(e) What was the surface velocity approaching the jam, and how far upstream was it — 1.0 m sec or less? (Timing the ice pieces over a known distance of, say, 30 metres is quite adequate).

(f) Are there any suitable storage locations for ice or water, or both, upstream of the jam?

(g) Observation should be repeated at these locations.

(h) How did the jam dissipate?

5.3 Summary of Monitoring

There are two periods when monitoring should be done:

(a) When the river is trying to form an ice cover (set out in Section 3).

(b) During the week prior to the flood date and the week following — as set out in Section 4.1.

The answers to questions posed in Section 5.1, (a) to (d), will indicate the benefits to be derived from any preventive and remedial techniques.

The cost of these, however, will depend on the solution chosen, based on the on-site observations made and answers given to questions in 5.2.1 to 5.2.3 inclusive.

It is a specialized task selecting the management plan most likely to succeed in any given situation and within any given budget. Success is dependent on accurate information from a good monitoring program.

6
Appraisal of Preventive and Remedial Measures

Prevention of ice jams is more effective than any remedial measures taken after the fact. For cases where the costs of prevention outweight the benefits, or where extraordinary weather conditions overload the system, removal of ice jams is required and the methods are outlined at the end of this section.

There are two basic types of measures for preventing jams:

(a) Weakening and breaking the ice cover into pieces small enough to flow freely.

(b) Controlling the flow of ice and water.

6.1 Weakening and/or Breaking

Before undertaking these activities, it is most important to know where the ice will go when it breaks. There needs to be a safe storage area, such as a lake, swamp or waterfall. Don't just move the problem downstream. This happened in 1982 on the Rideau River, where the Ottawa River normally provides enough storage for its ice. (Plates 3a and 3b). In 1982, however, the Ottawa itself was so ice covered that the Rideau's ice had nowhere to go and tried to flood back over the falls.

Start at the downstream end (normally the mouth), and work upstream so as to provide safety for workers and space for the broken ice to move into, away from the work area.

6.1.1 Dusting

To make the ice easier to break up into small pieces of one or two metres in diameter, it may be weakened first by dusting it with a dark substance like coal, cinders, or sand. Darker substances increase the rate of melting by about 10 mm/day in Ontario (11).

Cost for one application, covering one km of a 30 m wide river, and applied from the air by crop-dusting equipment, is estimated at $1,250 (17).

The effects of dusting may, however, be cancelled out by snowfall, in which case it has to be repeated. Often, also, there is insufficient time for the melting process to be completed sufficiently to break the ice up small enough to flow freely.

Plate 3a

Rideau Falls discharging into Ottawa River.

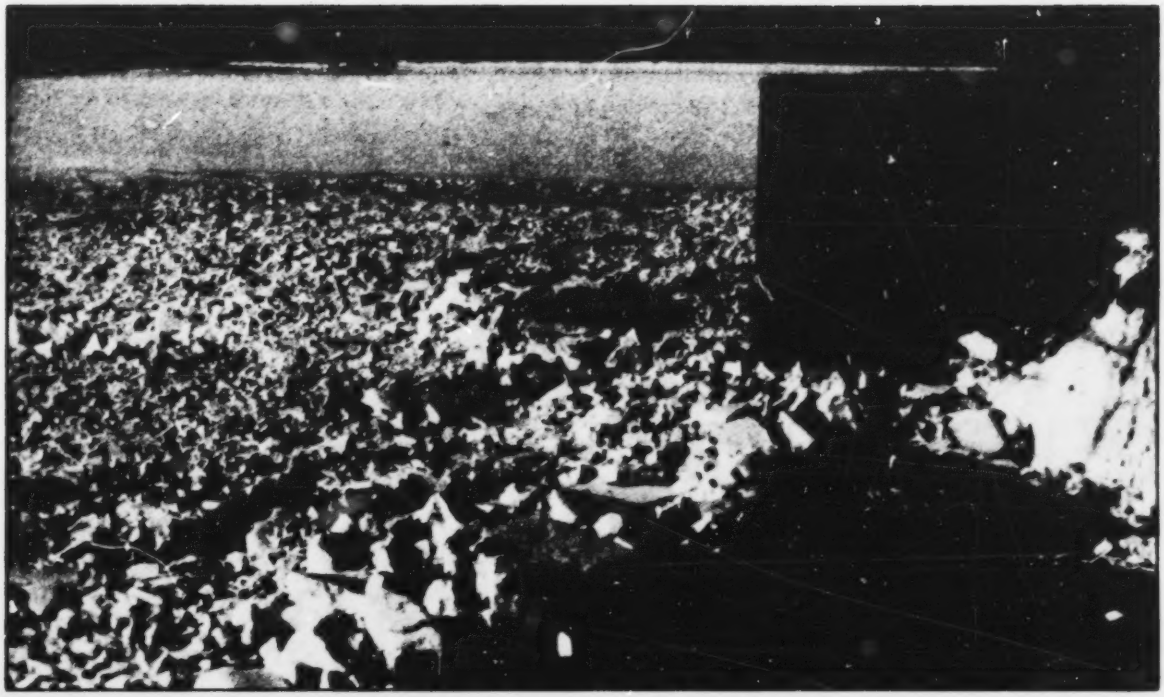


Plate 3b Looking downstream from Rideau Falls over the Ottawa River ice jam.

6.1.2 Ice Breaking by Blasting

Two essential prerequisites for this job are a properly trained crew and enough time. The time required for ice blasting is one eight-hour day per 1.6 km of ice cover (17).

To produce the desired results, the charge MUST be placed UNDER the ice at the correct depth which will depend on the charge weight (18). For example:

Distance below ice	Weight of charge	Diametre of hole created
1.2 metres	3.6 kg	2.7 metres
1.5 metres	7.3 kg	5.8 metres
1.8 metres	12.3 kg	8.8 metres

Best results are obtained by using ten to twenty charges, spaced one hole-diameter apart, detonated simultaneously.

The explosive used in the example cited was ANFO (Ammonium Nitrate in Fuel Oil). Its low detonation velocity (3,660 m/sec) works better than higher-speed explosives because it causes a wave-action to bend the ice, which is more effective at breaking than is a shattering action (18).

Where streams are more than 15 metres wide, two parallel lines of charges may be necessary in order to break the ice into pieces of one to two metres in diameter. Generally, the smaller the pieces, the more readily the ice will move through constrictions.

Success of blasting is limited by its inherent dangers, the possible lack of a suitable place to store the broken ice, and the fact that it may take too long.

6.1.3 Ice-Breaking by Boat

Normal ice-breakers press down on the cover to break it, and this works well as long as the cover is floating. A fairly recent experiment used a special plow on the front of a tug which forced the ice up and broke it by bending. Neither system works too well, though, if the ice is thick enough to hit bottom — although a regular ice-breaker can at least turn around and back through the ice stern first, provided it has twin screws. Then, the propellers can 'eat' a channel through the jam. The plow variety, however, tends to become a submarine if the ice is grounded.

Most commercial vessels are not satisfactory because they need three metres of depth for safe operation, and even that is not always sufficient, for the bow riding up on the ice drives the stern down, and boats with a two-metre nominal draft may then have problems in a depth of three metres. But small armored tugs specially designed for ice-breaking, which have only a one-metre nominal draft, have been used successfully in the Niagara River since 1964 (12).

An appreciable current to clear the ice from the work area is desirable, as is a safe place for the ice to flow into, of course. Then all that is required initially is to use the ice-breaker to create a narrow channel — or a 'lead' — wide enough for working in the deepest part of the river. Once this is established, the boat's wake widens the channel quite efficiently. It is not essential to clear the area completely, provided the pieces of ice are not larger than two metres in diameter.

Speed is of the essence, readiness is crucial. Often there is a period of only two to four days in which to prevent disaster. The boat should, therefore, be on-site, ready to operate within 24 hours or less. This is achieved by way of a retainer fee for stand-by periods, plus an operational charge for actual use. A captain experienced in ice-breaking is essential too.

Ice-breaking by boat will not be feasible, however, where the river is too shallow, if special vessels are not available, and if there are insufficient overhead clearances at bridges; it may not be feasible either where there is grounded ice.

6.1.4 Combination of Blasting and Breaking by Boat

The City of Ottawa (3) has carried out an effective program for many years, using the following system:

(a) Cut two slots, each 0.3 metres wide, parallel to each other, and generally parallel to the shore, along the edges of the normally-flowing sections of the river.

(b) Blast the slab between the slots — except of course, near bridges or utility crossings. In these places, small outboard-motor boats, with steel-protected hulls, provide the necessary wave action (described in Section 6.1.2).

(c) Timing, again, is crucial here. The flow has to be sufficient to push the ice from the Rideau out into the Ottawa River, but not so rapid as to get it all moving at once.

The disadvantage of this method is that several weeks of preparation are required. Occasionally also, the rate of change in weather is so fast that there is insufficient time to dispose of the ice cover.

6.1.5 Air-Cushion Vehicle (20)

Where the ice cover is hard, but not more than 0.7 metres thick, rapid progress can be made using air-cushion vehicles which create a pressure wave causing the ice to break by bending.

The costs, however, are high; so far only large craft exists, with no evidence of any designs being made for smaller vehicles suitable for Ontario's rivers. Other drawbacks: air-cushion vehicles cannot break grounded ice covers; their effectiveness decreases as the ice becomes softer; their free movement is inhibited by obstacles such as ice ridges and overhead bridges with limited clearance, because they need sloping ramps on the river banks to ascend, circumvent the obstacles, and descend into the river again.

6.2 Control

Controlling the excessive flow of ice and water to prevent flooding is achieved by constructing dams, ice booms, and weirs; or by providing ice-storage areas.

6.2.1 Control Dams

Although costly, control dams are the ultimate solution. By controlling the rate of change in level through controlling flows, the period of time over which break-up occurs can be lengthened. Thus, the amount of ice and water mixture can be controlled.

Control dams in the stream, rather than in the headwaters, are used mainly for controlling ice movement and some of the flow. The mechanism required here it to hold most of the ice coming from upstream, and release only controlled amounts of ice and water as and when the downstream area can accommodate them.

Control dams are expensive but reliable, as evidenced by the St. Lawrence Seaway and Power Project through 24 winters of operation. The system was designed to form an ice cover at velocities of up to 0.7 m sec over most of Lake St. Lawrence, where the flow can be adjusted to compensate for uncooperative weather conditions. Most of the ice then formed will stay on the surface rather than forming a hanging dam.

6.2.2 Ice Booms

Installed across a river, ice booms restrict the quantity and prolong the release of ice into potential jamming areas. (Plate 4). They work best when placed at right angles to the direction of the flow, and where velocities are equal to or less than one m/sec — the lower the better.

Ice booms can also accelerate the rate of ice-cover formation as well as helping retain it in the spring so more of the ice will melt in place rather than breaking up.

An ice boom should be designed to float up with the rising water levels, and to submerge also, so that it does not break if the force of the ice becomes too great for it to hold. Some ice will then pass over it; but, as the ice load decreases, the boom's buoyancy will return it to the surface and into effective action again.

Plate 4

Ice boom holding back various types of ice.

6.2.3 Weirs

These help to form ice covers, but are useful only where some form of restraint is provided, such as an ice boom. Without restraint, weirs are liable to spill their entire cover during break-up.

6.2.4 Ice Islands

Man-made or natural, islands provide something for the ice cover to push against after rising levels have removed the restraint formerly provided by the shore. They are not as flexible in their capabilities as ice booms, but have worked well in some instances.

6.2.5 Ice Storage

The Minesing Swamp on the Nottawasaga River and some of the disused channels on the Goulais River are good examples of ice storage areas. Disused channels (oxbows) are often located on the outside of sharp river bends. As ice tends to go straight ahead rather than following river bends, ice will fill these channels, which then act as safety valves for storing a good deal of broken ice.

6.2.6 Ice Removal as a Preventive Measure

Construction equipment can be used as a preventive measure to physically remove at least some of the potentially problem-causing ice. (For more on construction equipment for ice removal, see Section 6.3.1 following).

6.3 Remedial Ice Removal

In some cases, the cost of preventive measures may be too great to warrant the expenditure; in other situations, where prevention works well most of the time, an extraordinary sequence of weather events may, on occasion, still overload the system and cause a jam. Following are measures that may be effective after the jam has already occurred.

6.3.1 Construction Equipment

Ice can be removed physically with bulldozers, back-hoes and draglines. These have all been used successfully on the Ganaraska, Credit and Saugeen Rivers — both in prevention of and removal of jams. They are relatively cheap, but are effective only in locations where the ice cannot affect their operation and where they can actually reach the jam — which is often not possible. While these types of equipment may be effective on small streams and rivers, this is not usually the case in larger waterways.

6.3.2 Blasting Under a Jam

This works best by starting at the downstream end of the jam and working upstream. Placing the charges may be dangerous, and the results will depend on whether the liberated jam has a safe place to go. Ideally, the jam should be released slowly — or else it may result in another jam downstream.

Bombing, howitzer shells, or bazookas are subject to the same drawbacks, and are not likely to work unless they can be detonated under the ice.

7
Principles of Ice Control

Some of the principles of ice control may be summarized as follows:

7.1 Ice cover protects the water from super-cooling, decreases the total volume of ice produced and prevents the formation of slush ice from snow in the open water, therefore:

CREATE ICE COVER AS SOON AS POSSIBLE OVER AS MUCH OF THE RIVER SURFACE AS POSSIBLE

7.2 Ice cover breaks up because of a rapid rate of change in water level and due to increases in velocity, therefore:

CONTROL ICE MOVEMENT BY CONTROLLING FLOW AND HENCE VELOCITY.

7.3 Ice jams normally last a few days only, therefore:

BY SLOWING THE RATE OF RISE IN LEVELS, AND HENCE THE INCREASE IN VELOCITY, THE AMOUNT OF ICE BROKEN PER UNIT LENGTH OF RIVER CAN BE REDUCED. THERE IS THEN LESS ICE AND LESS WATER COMPETING FOR SPACE IN THE CONSTRICTED SECTIONS AND, THEREFORE, LESS FLOODING.

7.4 When flows cannot be controlled,

PROVIDE ICE MOVEMENT CONTROL SUCH AS ICE BOOMS OR ICE STORAGE AREAS.

7.5 Ice jam floods can be costly and dangerous to break. Therefore:

PREVENTION OF JAMS IS MORE EFFECTIVE THAN ANY OF THE CURES.

7.6 Solving an ice problem in one municipality may merely move it downstream to become someone else's problem. Therefore:

MAKE SURE THE JAMMED ICE CAN BE RELEASED TO A LAKE OR OTHER LARGE STORAGE AREA.

WHEREVER POSSIBLE, ICE BREAKING SHOULD BEGIN AT THE RIVER MOUTH AND WORK UPSTREAM.

7.7 Ice covers break most readily by bending and, once broken, the smaller the piece size the better. Therefore:

WAVE ACTION, EITHER BY BOAT OR AIR CUSHION VEHICLE, WORKS BEST.

7.8 As spring approaches and the days get longer, there is an increase in water supply, a rise in water levels, and an increase in velocity. Therefore:

THE PORTIONS OF THE RIVER WHICH FROZE OVER LAST WILL LOSE THEIR ICE COVER FIRST.

WHEREVER SURFACE VELOCITIES EQUAL OR EXCEED 1 M SEC, SOME BREAK-UP IS TO BE EXPECTED.

7.9 Every watershed has a critical flow which will cause a major break-up. Based on preliminary data, it appears that:

THE CRITICAL FLOW IS ABOUT 60% OF THE OPEN WATER 100-YEAR FLOW, WITH VARIATIONS OF BETWEEN 50% AND 70% BEING LIKELY DUE TO ICE QUALITY AND WEATHER SEQUENCES.

8 Selected References

There are many papers relating to design problems and research projects but few met the criteria for this manual, which were that:

(a) They must be relevant to the climatic conditions of Ontario;

(b) They must have similar topographical conditions to those in Ontario;

(c) They must have direct application to operational ice problems for use by Resource Managers.

Relevant references are arranged by subject.

8.1 Key to Abbreviations in Succeeding Paragraphs 2 to 5

I.M.S.P.
Ice Management Seminar Proceedings — January 30, 1980 — Produced by the Ontario Ministry of Natural Resources, Southwestern Region, London

W.H.R.R.I.
Proceedings of the Workshop on Hydraulic Resistance of River Ice — September, 1980 Produced by the National Water Research Institute (formerly C.C.I.W.), Burlington, Ontario — edited by G. Tsang and S. Beltaos

N.R.C.
National Research Council, Canada.

I.A.H.R.
International Association of Hydraulic Research Ice Symposia
— Iceland, 1970; Hanover, New Hampshire, 1975;
— Sweden, 1978; Quebec, 1981

C.C.R.E.L.
Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire

C.J. of C.E.
Canadian Journal of Civil Engineers

A.S.C.E.
American Society of Civil Engineers

I.H.D. — W.M.O.
International Hydrologic Decade combined with the World Meteorological Association, Banff, 1972

8.2 Case Studies of Chronic Problem Rivers in Ontario

REFERENCE NUMBER

THAMES RIVER FLOOD — MARCH, 1979. I.M.S.P., 1
by B. Bennett, LOWER THAMES VALLEY C.A.
History of major ice-jam related floods in 1951, 1965, 1968 and 1979 in detail. Comments on the use of dynamite and an ice-breaking tug. Solutions required upstream of Chatham.

MOIRA RIVER — BELLEVILLE, I.M.S.P. 2
by K. Lathem, Crysler and Lathem Ltd.
Chronic problems in Belleville. Large quantities of sheet ice move into lower velocity areas where "hanging dam" conditions prevail, i.e., the supply of ice and water is much faster than channels can discharge it into the Bay of Quinte. Ice storage works constructed in 1977-78 for about $2.5 million. Preliminary results are mostly satisfactory, but evaluation is still lacking.

"RIDEAU RIVER" — OTTAWA 3
by W. Frietag, City of Ottawa
The City of Ottawa undertakes an annual ice-breaking program to alleviate flooding on the Rideau River at a cost of approximately $125,000.

Keys are cut in the ice at bridges and other locations where blasting is prohibited. Broken ice is flushed downstream by increased flows from an upstream reservoir. Mechanical saws, dynamite, boats and up to 30 men are involved and careful planning is essential.

8.3 How and Where Ice Jams Form and Collapse

8.3.1 During Freeze-up

REFERENCE NUMBER

WINTER REGIME OF RIVERS AND LAKES, CCREL, APRIL, 1971 — 4
MONOGRAPH III — Bla
by B. Michel — Laval U., Sept. 1980

This is the most comprehensive publication for understanding ice formation processes in their various forms and the behaviour of rivers and lakes during freeze-up and break-up.

RIVER ICE HYDRAULICS, W.H.R.R.I. — 5

A discussion of resistance of ice covers, ice jams at break-up and ice cover formation. An important missing element was cited as "lack of ice jam thickness measurements". Of particular value is Figure 3 on Page 189, which shows the "universal stability diagram" for ice covers during freeze-up, break-up (jam) and break-up (solid cover).

ST. LAWRENCE POWER PROJECT ICE MANUAL. — 6
ONTARIO HYDRO — 1968, UNPUBLISHED DOCUMENT
by D.M. Foulds

Design criteria and operating performance are compared for a period of about 20 years. In general, the 0.7 m sec average velocity for ice cover formation has worked well. Some years the ice cover was smoother than expected and in a few years the opposite, depending on weather conditions at the time of formation. Operating instructions are given for recognizing likely jamming conditions.

STUDIES OF RIVER AND LAKE ICE, Volumes 2, 3 and 4 — 7
ONTARIO HYDRO, Unpublished — I.H.D. Data

Three years of weather and ice data are available for the Niagara River between Fort Erie and the Falls. Extensive information is provided on frazil formation, anchor ice and ice volumes, but there are few conclusions.

8.3.2 During Break-up

REFERENCE NUMBER

"MECHANICS OF ICE JAMS" I.M.S.P. — 8
by D.B. Hodgins, J.F. MacLaren Ltd.

This is a good summary paper of the state of the art and contains an extensive bibliography (57 pages), some of which may be misleading. Unresolved problems relate to the strength of unconsolidated ice jams, their thickness and roughness.

"FROUDE CRITERION FOR ICE BLOCK STABILITY" — 9
GLACIOLOGY JOURNAL, VOL. 13, No. 68, 1974, by G.D. Ashton — CCREL

Stability analysis on floating ice blocks are well set out here, and it is really an extension and improvement on the work of Uzuner and Kennedy.

"RIVER ICE JAMS", THEORY, CASE STUDIES AND APPLICATIONS — January, 1982 — 10
by S. Beltaos, NATIONAL WATER RESEARCH INSTITUTE

A "State-of-the-art" summary of what can be done to predict flood stages at this time. The limitations are clearly set out and it seems unlikely that these will be resolved in the near future.

"BREAK-UP AND CONTROL OF RIVER ICE", I.A.H.R. — 11
by G.P. Williams — N.R.C.

Good paper for the Ontario scene. Cites the importance of variable weather sequences, the added problems of northward flowing streams. Information on "dusting" to accelerate break-up.

"NIAGARA RIVER ICE MANUAL", Ontario Hydro, 1964 — 12
by D.M. Foulds, Unpublished.

Historical summary of ice problems and the weather sequences which caused them. Worst problems caused by weather variability from cold to warm and back again with the attendant storms being the most significant. Operating instructions for monitoring ice movements in order to recognize major problems developing, preventative and remedial measures.

REFERENCE NUMBER

"NIAGARA RIVER ICE CONTROL", EASTERN SNOW CONFERENCE, February 1967, by D.M. Foulds. 13

Operating experiences during some horrendous storms, ice removal by ice breakers and by manipulation of river levels and velocity, success of ice boom.

DYNAMICS OF ICE FORMATION IN THE UPPER NIAGARA RIVER 14
I.H.D. — W.M.O., Banff 1972,
by R.S. Arden and T.E. Wigle

Results of part of the studies referred to in reference 7 above. Excellent pictures of frazil and a good description of the difficulties in ice research, especially in relation to trouble-free operation of instruments. Recording water temperature thermometer and net radiometer instruments give good estimation of onset of frazil formation and anchor ice.

"SOUTHERN ONTARIO ICE JAM STUDIES", O.M.N.R., C.A.W.M.B. 15
by D.M. Foulds

Report on the very unseasonal break-up of Southern Ontario streams in February, 1981.

8.4 Effects of Ice Jams on Water Levels

Caution is advised in reading the literature and in trying to apply results from one area to another. There is a great variation in effects, depending on such variables as the slope of the water surface, the steepness and height of the river banks, the supply of ice and the prevailing climate and its variability. For example, W.L. Knowles speaks of rises of 1 to 2 metres on the Thames, whereas D.M. Foulds at Niagara speaks of 20 metres (13).

"EFFECTS OF RIVER ICE ON STAGE", I.M.S.P. 16
by W.L. Knowles, J.F. MacLaren Ltd.

In rivers with very mild gradients, ice accumulation as far as 5 to 10 miles downstream can have an effect on river stage at a gauging station. Illustrations are presented for Dresden, Thamesville and Chatham. Utilization of frequency data for predicting 1-in-100 year stage levels or delineating the 1-in-100 year floodway must receive careful evaluation.

8.5 Remedial Measures

REFERENCE NUMBER

"METHODS OF REMOVING ICE JAMS", I.M.S.P. 17
by S.L. Denhartog, C.C.R.E.L.

A good summary paper on the appropriate times for trying to remove ice jams, as well as the possible consequences. Methods for removal are given together with some costs for using machinery, dusting, ice breaking, ships and blasting. Advantages and disadvantages are discussed.

"USE OF EXPLOSIVES IN REMOVING ICE JAMS 18
C.C.R.E.L., M.P. 1021, 1970
by G.E. Frankenstein

Excellent practical information on how to blast ice covers for maximum cracking. Optimum depths for and size of charges, speed of explosive (low) and resulting hole sizes. Break-up of about 1.6 km crew day is maximum.

"BLASTING SHEET ICE AND ICE JAMS", I.M.S.P. 19
by D. Mairs, C.I.L., Toronto

Methods of blasting, advantages of various types of explosives and detonation, proper handling and safety techniques.

"AIR CUSHION VEHICLES" (ACVs), I.M.S.P. 20
by R. Wade, Canadian Coast Guard

"Rates of 25 km hr break-up of 1 metre thick ice were obtained with a 50-tonne vehicle 20 m long by 10 m wide"; i.e., good for big rivers but not small ones. Current models are too large and too expensive to build and operate unless they can be used for other purposes throughout the year.

"SPECIFICATIONS FOR ACVs", I.M.S.P. 21
by D. Jones

Good proposal for smaller vehicles, but none available or in production.

"USE OF ICE BREAKING BOATS", EASTERN SNOW CONFERENCE, 1967 22
by D.M. Foulds

Used on the Niagara River and also used in the Lower Thames for many years.